Evaluation of deriving fire cycle of forested landscape based on time-since-fire distribution

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Abstract: Estimation of fire cycle has been conducted by using the negative exponential function as an approximation of time-since-fire distribution of a landscape assumed to be homogeneous with respect to fire spread processes. The authors imposed predefined fire cycles on a virtual landscape of 100 cell ×100 cell, and obtained a mosaic composing of patches with different stand ages (i.e. time since fire). Graphical and statistical methods (Van Wagner 1978; Reed *et al*. 1998) were employed to derive fire cycle from the virtual landscape. By comparing the predefined and the derived fire cycles, the two methods and tested the effects of sample size and hazard of burning (i.e., stand's susceptibility to fire in relation to its stand age) were evaluated on fire cycle deviation. The simulation results indicated a minimum sample size of 10 times of the annual burnt area would be required for partitioning time-since-fire distribution into homogeneous epochs indicating temporal change in fire cycle. Statistically, there was significant difference among the imposed and the derived fire cycle, regardless of sample sizes with or without consideration of hazard of burning. Both methods underestimated the more recent fire cycle without significant difference between them. The results imply that deviation of fire cycle based on time-since-fire distribution warrants cautious interpretation, especially when a landscape is spatially partitioned into small units and temporal changes in fire cycle are involved.
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Introduction

Fire has been the dominant disturbance and responsible for much of the structure and function of boreal ecosystems (Wein and MacLean 1983; Johnson 1992). Among the components defining fire regime (i.e., a combination of four components, namely intensity, frequency, seasonality and size), fire cycle (van Wanger 1978) or fire rotation (Heinselman 1973), is an indicator of fire frequency measuring the time (years) required to burn an area equal in size to the area under consideration.

Fire cycle has been an important component in maintaining many ecosystems on earth in particular boreal ecosystems for the past 10 000 years since the last glaciation (Payette *et al.* 1985). Along the migration of species from south and other refugees of glacier, ecosystems adapted to the various fire regimes in the boreal region but they are not necessarily in equilibrium with the climate (Overpeck *et al*. 1990; Campbell and McAndrews 1993). Studies revealed a complex interaction among landscape, fire regimes, and vegetation types (Bergeron *et al*. 1993; Suffling 1995; Hely *et al*. 2001; Li *et al*. 2005). Changes in fire cycles would have significant consequences on landscape pattern by affecting regenerating pathways of forest after fires. Interactions of fire cycle and species' reproductive characteristics could determine vegetation distribution pattern of a landscape (Suffling *et al*. 1988; Bergeron and Dansereau 1993; Johnson at al. 1995; Suffling 1995; Gauthier *et al*. 1996).

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Practically, time-since-fire distribution has often been used to derive fire cycle (Van Wagner 1978). The derived fire cycle, commonly through a fitness of the negative exponential function, has been utilized to assess the influence of human activities and climate change on fire regime (Johnson 1979, 1992; Johnson *et al*. 1985; Baker, 1989; Johnson *et al*. 1990; Masters 1990; Johnson *et al*. 1991). Such an approach has provided valuable insights in understanding fire regime, but there are outstanding issues over this approach.

First, the negative exponential function is an approximation of time-since-fire distribution of a landscape subject to random, periodic fires and uniform flammability with stand age (Van Wagner 1978; Johnson and Van Wagner 1985; Johnson *et al*. 1994). Thus, the landscape is assumed to be homogeneous with respect to fire initiation and spread processes. Rarely is this the case in reality. For instance, biophysical factors such as fuel buildup in a stand may affect fire initiation and spread (Agee *et al*. 1987; Bergeron 1991; Johnson 1992). Second, fire cycle is a relative term that depends on burnt area, time period, and total area of interest (Li 2002). Studies have derived fire cycles from areas ranging from a few thousand hectares to thousands of square kilometers (Baker 1989; Johnson *et al*. 1991; Masters 1990). If a sample area is too small, one fire incident could burn over the entire area of interest, and derived fire cycle could be misleading. Thus, it would be of great interest in understanding how different sample sizes and landscape heterogeneity affect fire cycle deviation.

Recently, Reed *et al*. (1998) developed an improved statistical methodology to derive fire cycle in particular concerning temporal changes in fire cycle using time-since-fire distribution. The method took into consideration the fact that surviving stands originating in earlier epoch have been subjected to the more recent fire cycle. They argued that the previous method (Van Wagner 1978; Johnson *et al*. 1994) overestimated fire frequency

of the more recent epoch because it ignored the surviving older stands.

In this study, we adopted a simple model and our objectives were to: 1) evaluate the effects of sample size and no-random process of fire spread on fire cycle deviation; and 2) compare the two methods, graphical (Van Wagner, 1978; Johnson *et al*. 1994) and statistical (Reed *et al*. 1998), of interpreting fire cycle. The approach is a “fire cycle game” (Van Wagner 1978), a reverse procedure that imposes a predefined fire cycle on a virtual landscape and consequently compares with that derived from the resultant time-since-fire distribution.

Methods

The model was adapted from a previous study investigating the impacts of forest clearance on landscape pattern, a somewhat similar process with fire disturbance in terms of landscape configuration (Zhang *et al*. 2002). The model was developed in the ARC/INFO GIS platform and it composes of three components: a model simulator, map output, and a package to analyze landscape indices. The model simulator requires three parameters, fire cycle, disturbance hazard, and annual variation in disturbed area (i.e., a constant or derived from a distribution). Fire cycle was defined as the number of years required for fire to burn an area equal to the entire area under consideration (Van Wagner 1978), and hazard of burning referred to a stand’s susceptibility to fire in relation to its stand age (i.e., time since last fire; Li *et al*. 1996). Map output is a subroutine to generate maps that could be used to further analyze the spatial pattern in a landscape. The outputs might be derived following the initial instruction (i.e., by different age-class interval) or the actual stand age during the model running procedure. An analysis package was developed to quantitatively describe landscape structure. Two simulations, which differed in hazard of burning, were carried out on a virtual landscape with a size of 100 cell ×100 cell.

In the first simulation, initiated fire spread into its four neighboring cells with equal probability regardless of their stand ages. Fire initiation, however, was limited to and randomly started in a stand with ages of at least 100 years considering that old stands were more flammable in reality (Agee and Huff, 1987). In case that the initiated fire was ‘trapped’ in a cell, i.e., all four neighboring cells were disturbed at the same running steps, the actual burned area was recorded. Fire randomly started in another cell with a stand age of at least 100 years and spread until it was ‘trapped’ or ‘burned’ an equivalent pre-determined number of cells.

The second simulation was similar but considering hazard of burning. For the sake of simplicity, hazard of burning for a one-year-old stand was defined as 0.01 and linearly increased to 1 when the stand reached 100-year–old and older. An initiated fire spread into its four neighboring cells with probability proportional to the stand ages of the cells. Thus, the virtual landscape was not homogeneous with respect to fire spread process.

For each simulation, the model was first run on a homogeneous landscape of 100 cell ×100 cell for 500 years with fire cycle of 100 years. On average, a cell could have been burned five times during this period, and that was intended to remove any possible effects from the age structure of the initial landscape. The model was then run for another 300 years with 10 replicates. Fire cycle was 100 years for the first 150 years of model running time (i.e., epoch 2 fire cycle deviation) and was changed to 200 years afterwards (i.e., epoch 1). Longer fire cycle in recent decades has been evident in various studies (Suffling *et al*. 1982; Bergeron *et al*. 2001). Disturbed area at each time step was generated from the exponential distributions (Baker 1989; Li *et al*. 1999) with means of 100 and 50 cells. Thus, the number of cells burned in each time step varied and predefined, but over time, it ensured fire cycles of 100 and 200 years for epoch 1 and 2, respectively. All cells were grouped by their stand ages at ten-year intervals, and time-since-fire distributions were developed for randomly selected blocks of 10×10, 20×20, 25×25, 30×30, 40×40, and 50×50 cells and entire landscape (i.e., 100 cell×100 cell), respectively.

Graphical (Van Wagner 1978; Johnson *et al*. 1994) and statistical (Reed *et al*. 1998) methods were employed to derive fire cycles from the resultant time-since-fire distributions. The graphical procedure was based on the logarithmic plot of the cumulative area with a stand age greater than *t*, against t. The distributions were first partitioned into 2 epochs corresponding to the implemented change of fire cycle in year 150 of the model running time, and fitted into the negative exponential model. The graphical approach estimates fire cycle as being the simple mean of the stand age of a landscape, or the slope of the semi-log cumulative distribution plot (Johnson *et al*. 1994). Statistical method (Reed *et al*. 1998) expressed the distribution A(t) as following:

$$A(t) = \exp(-\lambda_1 t) \qquad 0 \leq t < P_1 \qquad (1)$$

$$A(t+1) = \exp[-\lambda_1 P_1 - \lambda_2 (t - P_1)] \qquad P_1 \leq t \qquad (2)$$

where, t is the age-class or time-since-fire, P_1 the date of the change point (i.e., 150 years in this study), and $1/\lambda$ is fire cycle. The parameter λ was estimated by using the maximum likelihood estimate. ANOVA was used to compare the difference among fire cycles derived from different sample sizes and those from the two methods, and *t*-test for the difference between the model input of fire cycle (i.e., 200 and 100 years for epoch 1 and 2, respectively) and those derived from the resultant time-since-fire distributions (Zar 1984).

We should point out: 1) The input variables were arbitrary. For instance, hazard of burning was defined as a linear increase from 0.01 for a one-year-old stand to 1 for stands reaching 100-year-old and older. The results might have been slightly different if we had defined a different relationship between stand age and stand’s susceptible to fire, but here we were interested in how different was the derived fire cycle in a heterogeneous landscape compared to that in a homogeneous once with respect to fire spread process. 2) There were conflicts between the input simulation conditions and the assumptions for the methods of deriving fire cycle from the resultant landscapes in this study. Most studies utilized the negative exponential function as an approximation of time-since-fire distribution for fire cycle deviations on a forested landscape. Such approximation assumed that landscape was homogeneous with respect to fire spread processes as we parameterized in simulation 1. In reality, fire occurrence likely increased with stand age. When hazard of burning was considered in simulation 2, Weibull distribution had been proposed but few researchers used it to derive fire cycle (John *et al*. 1994). One of the objectives of this exercise was to evaluate the reliability of the derived fire cycles in studies using the negative exponential function rather than Weibill distribution as it

was supposed to.

Results

The time-since-fire distributions are shown in Fig. 1 and 2, presenting the results for simulation 1 (i.e., fire spread was a random process regardless of stand age) and simulation 2 (i.e., fire spread was relating to stand age) of different sample sizes ranging from 10 cell ×10 cell to 50 cell ×50 cell. The distribution of the entire landscape (i.e., 100 cell ×100 cell) is similar to that of 50 cell ×50 cell. Visual examination can reasonably identify the change point of the imposed fire cycles (i.e., from 100 to 200 years in the simulation) on the distributions derived from sample sizes larger than 625 (25×25) cells, regardless of hazard of burning.

The derived fire cycles are listed in Tables 1 and 2, and they are significantly different from the predefined ones (i.e., 200 and 100 years for epoch 1 and 2) with few exceptions (i.e., sample sizes smaller than 20 cell ×20 cell due to large standard deviations) (t-test, $P<0.05$). The derived fire cycles are not significantly different regardless of sample size and hazard of burning. However, smaller sample sizes result in larger variations in the derived fire cycles, indicated by the standard deviations of 10 replicates. Comparisons yield no significant differences (ANOVA, $P>0.05$) for Epoch 1 and the differences are significant (ANOVA, $P<0.05$) for Epoch 2 among the derived fire cycles using the two methods. Both the graphical and statistical approaches underestimate fire cycles of the more recent epoch (Epoch 1 in Tables 1 and 2). The graphical approach overestimates fire cycle for Epoch 2, while the statistical approach underestimates fire cycle of the same epoch.

Discussion

In reality, fire cycle could only be derived from fragmented landscapes. The simulation results indicate that there are not significantly differences among fire cycles derived from various sample sizes, with or without consideration of hazard of burning (ANOVA, $P>0.05$) (Table 1, 2). However, it is problematic to partition a time-since-fire distribution into homogeneous epochs when sample areas are too small (Figs. 1, 2). It seems that the sample area has to be at least ten times of the annual burnt area for a reasonable partition corresponding to the implemented temporal changes in fire cycle. Large variations in the derived fire cycles, indicated by the 10 replicates, imply that the estimated fire cycles may not be representative at the regional scale if a study area is too small (Table 1, 2). This poses a serious obstacle in fire history reconstruction studies because changes in land cover (e.g., clearing forest for cultivation) may have erased evidence of previous fire events (Weir *et al*. 1998; Weir *et al*. 2000), in particular when a landscape is spatially partitioned into small units (Heinselman, 1973; Baker, 1989) and temporal changes in fire cycle is involved in a study.

Table 1. Derived fire cycles (10-replicates in years) without consideration of the influence of stand age on fire spread

Items	Graphical method (Van Wagner 1978)							Statistical method (Reed *et al*. 1998)						
	Sample size(cells)							Sample size(cells)						
	100×100	50×50	40×40	30×30	25×25	20×20	10×10	100×100	50×50	40×40	30×30	25×25	20×20	10×10
Epoch 1	212	231	166	184	167	197	139	200	208	174	196	167	199	121
	179	189	140	221	207	238	378	178	182	150	222	206	284	191
	179	159	156	111	147	177	234	185	167	150	113	164	154	222
	172	170	201	150	138	153	96	170	165	221	138	156	180	153
	187	185	174	187	149	176	195	170	154	150	156	152	150	134
	167	177	180	129	207	185	210	170	198	232	135	205	163	167
	183	185	210	198	170	265	145	161	154	190	144	154	165	171
	183	171	205	135	164	271	706	187	183	182	144	156	274	494
	174	168	178	166	197	181	491	159	150	177	165	217	164	446
	183	196	156	148	193	176	52	166	180	133	132	159	130	73
Mean	182	183	177	163	174	202	265	175	174	176	155	174	186	217
s.d	12	20	23	34	26	41	203	13	19	32	33	25	52	140
Epoch 2	142	146	138	147	124	161	116	90	94	93	86	76	89	87
	129	132	117	144	139	166	143	79	82	73	79	81	79	104
	139	132	130	110	123	110	172	84	85	89	92	76	54	99
	126	126	133	112	122	142	102	78	77	69	81	76	112	89
	123	117	118	120	118	118	93	71	73	73	72	78	69	60
	129	139	150	112	134	120	133	80	84	87	67	67	62	86
	115	114	117	104	120	120	98	68	73	57	69	72	95	65
	130	128	130	111	110	136	155	76	73	74	74	63	59	55
	123	117	143	139	138	114	142	80	79	88	82	74	58	51
	125	128	107	118	126	86	87	80	77	84	75	87	49	61
Mean	128	128	128	122	125	127	124	79	80	79	78	75	73	76
s.d.	8	10	13	16	9	24	29	6	7	11	8	7	21	19

Notes: Epoch 1 and 2 refers the recent 150 years and the time periods of 150 years ago with predefined fire cycles of 200 and 100 years, respectively.

Table 2. Derived fire cycles (10 replicates in years) with consideration of stand's susceptibility to fire relating to its stand age.

Items	Graphical method (Van Wagner 1978)							Statistical method (Reed *et al.* 1998)						
	Sample size (cells)							Sample size (cells)						
	100×100	50×50	40×40	30×30	25×25	20×20	10×10	100×100	50×50	40×40	30×30	25×25	20×20	10×10
Epoch 1	222	213	236	302	206	254	163	196	193	191	234	176	253	165
	181	188	114	208	202	175	598	183	181	163	165	194	160	722
	164	152	167	210	152	123	63	153	141	113	212	149	125	62
	188	155	287	109	149	118	277	167	143	270	108	131	108	252
	218	228	240	144	165	278	3738	167	191	172	136	132	180	274
	170	150	152	175	129	182	223	166	157	140	152	143	143	184
	196	197	177	219	184	178	62	177	173	170	171	179	165	182
	171	171	173	201	149	230	216	174	163	202	184	192	223	376
	190	185	140	341	218	157	294	173	173	134	292	181	164	235
	191	169	140	158	193	199	213	170	150	123	146	177	179	220
Mean	189	164	169	191	155	170	563	173	167	168	180	165	170	267
s.d	19	28	56	72	31	55	1178	12	19	46	55	25	45	189
Epoch 2	134	129	138	139	131	150	124	75	71	83	72	81	73	57
	127	132	128	121	118	102	116	71	77	71	74	53	42	22
	129	124	116	136	137	125	100	86	86	91	65	99	92	104
	125	119	145	97	112	84	107	81	87	72	78	81	68	51
	113	120	113	103	99	109	134	60	65	58	45	52	52	67
	134	128	129	127	117	113	134	95	92	103	84	84	77	77
	118	115	116	105	122	120	81	68	68	66	62	76	77	37
	116	116	109	113	105	96	145	63	67	45	55	47	27	61
	118	116	102	153	128	131	109	62	59	54	69	74	83	47
	120	111	100	111	121	130	132	68	66	65	60	68	74	58
Mean	123	121	110	109	119	103	105	73	74	71	66	72	67	58
s.d.	7	7	14	19	12	20	20	12	11	18	12	17	21	24

Notes: Epoch 1 and 2 refers the recent 150 years and the time periods of 150 years ago with predefined fire cycles of 200 and 100 years, respectively.

Comparisons among the derived fire cycles indicate that hazard of burning (i.e., stand's susceptibility to fire in relation to its age) is not a significant factor in fire cycle deviation using time-since-fire distribution (Table 1, 2). That might result from the indiscriminative nature of fire spread. Forest fire burns continuously over the landscape, and a stand adjacent to a burning one has a higher probability of being burnt than a stand far away, regardless of its stand age. This contagion effect (Li *et al*. 1996; Reed *et al*. 1998; Li 2002) may result in significant difference in landscape configuration and overall stand ages of the landscape but not affect fire cycle deviation from time-since-fire distribution.

It is a surprise that the derived fire cycles using the two methods are not significantly different for the more recent epoch (Epoch 1 in Table 1, 2). Reed *et al*. (1998) argued that surviving stands are subject to different fire cycles and the graphical method (Van Wagner 1978; Johnson *et al*. 1994) likely underestimated fire cycle of the more recent epoch. However, once a time-since-fire distribution is partitioned into homogeneous epochs, fire cycle for each epoch is independently derived from stands that only record the most recent fire events. Mathematically, the statistical method (Reed *et al*. 1998) considers one age-class more than the graphical method does (Johnson *et al*. 1994). It does not necessarily cause significant difference as it has been demonstrated by the rather large confidence intervals (Reed *et al*. 1998). Moreover, identification of change point on a time-since-fire distribution is a somewhat subjective exercise, and both semi-log plots and statistical approach have limited power because of few classes in the distribution, and the change point may shift one age-class either way.

The two methods derive significant different fire cycles for epoch 2 (Table 1, 2; ANOVA, $P < 0.05$). The graphical method overestimates fire cycle (Table 1), while the statistical method underestimates it (Table 2). The former procedure partitions the entire landscape into two fractions corresponding to the recent and previous fire cycles. When the fraction burnt in the more recent epoch (i.e., Fig. 1) underestimates its fire cycle, fire cycle in epoch 2 is bound to be overestimated because the total burn area is a constant. The statistical approach only uses the surviving stands to estimate the fire cycle of the previous epoch (Fig. 2). That implies that the young stands are only subject to the most recent fire cycle, and the younger stands that have been subject to the previous fire cycle and whose evidence has been eliminated by the recent fire events, are ignored. Thus, it overestimates the fire frequency (i.e., underestimate fire cycle).

Regardless of the tested variables (i.e., sample size, hazard of burning) and methods in the simulation, the derived fire cycles are significantly different from the redefined ones (i.e., 200 and 100 years for epoch 1 and 2, respectively; *t*-test, $P<0.05$). The difference might result from approximation of time-since-fire distribution to the negative exponential function (Van Wanger *et al*. 1978) and fire's contagion effect (i.e., stands adjacent to burning ones have higher probability of burning than ones far away from the burning stands; Li and Apps, 1996; Reed *et al*. 1998). Perhaps, the root cause of the difference is because time-since-fire distribution only records the most recent fire event in each unit of a landscape.

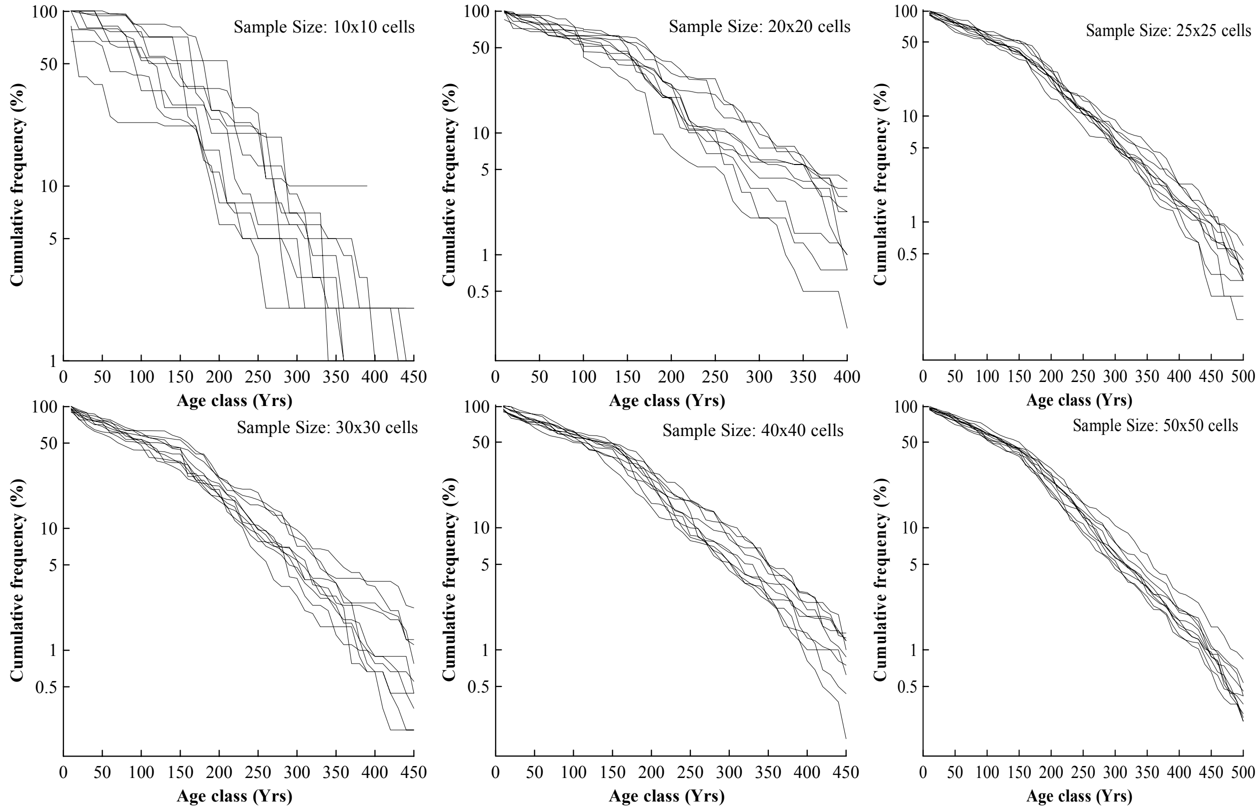

Fig. 1 Time-since-fire distributions of the simulated 10-replicate landscapes on which initiated fire spread into its four neighboring cells with equal probability regardless of their stand ages

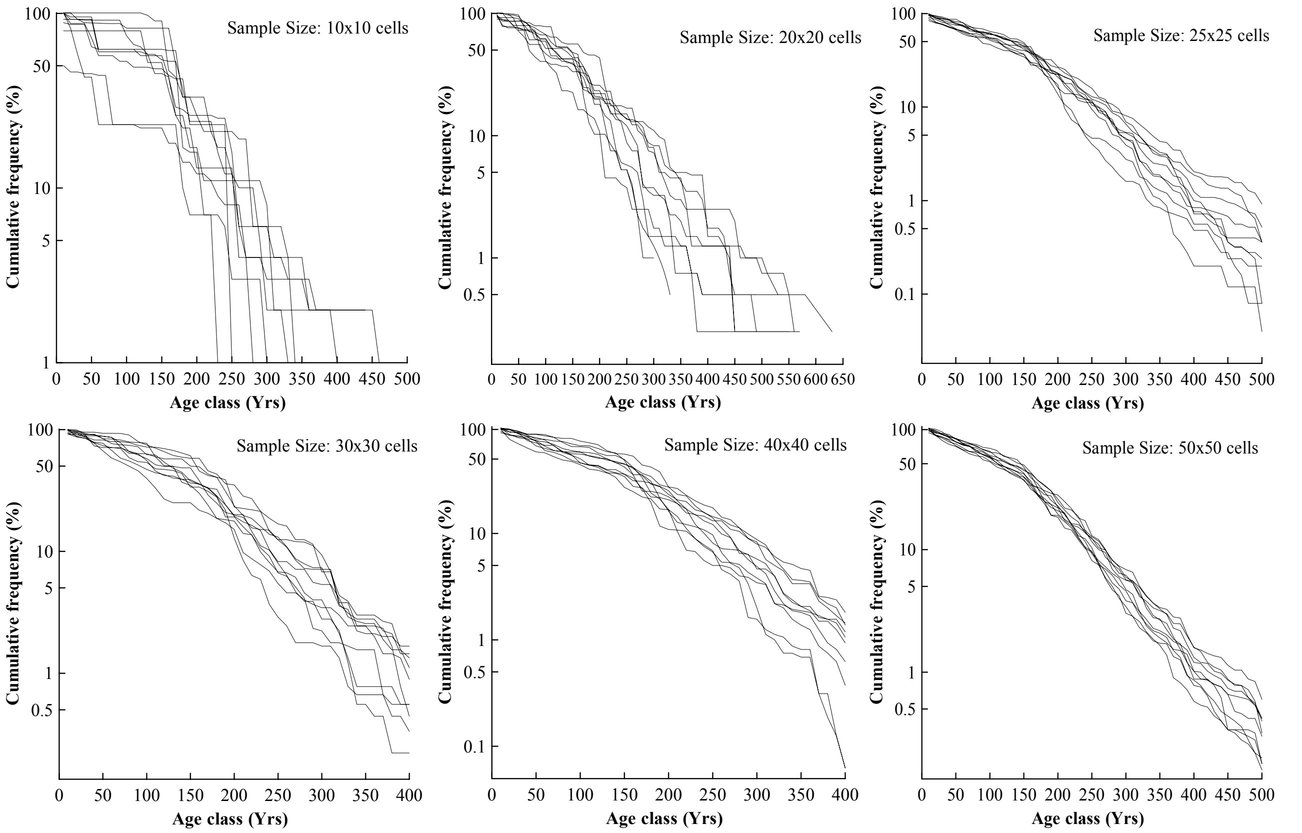

Fig. 2 Time-since-fire distributions of the simulated 10-replicate landscapes on which fire spread into its four neighboring cells with probability proportional to the stand ages of the neighboring cells

Time-since-fire distribution provides a useful means to understand both spatial and temporal changes in fire cycle (Baker 1989; Masters 1990; Johnson *et al*. 1991). Human activities (e.g., fire suppression) and climate change have dramatically altered fire regime of the past century (Johnson *et al*. 1991; Bergeron *et al*. 1993; Larsen 1996; Weir *et al*. 1998; Weir *et al*. 2000), and potential climate warming would further change it considerably (Weber *et al*. 1997; Flannigan *et al*. 1998). Monitoring of fire activities corresponding to climate change has to focus on rather large and ecological uniform landscapes because smaller sample sizes may provide inaccurate indications of changes in fire regime.

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